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EXTENSIONS OF WILSON'S LEMMA AND THE AX-KATZ THEOREM

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ABSTRACT. A classical result of A. Fleck states that if p is a prime, and $n > 0$ and r are integers, then

$$\sum_{k \equiv r \pmod{p}} \binom{n}{k} (-1)^k \equiv 0 \pmod{p^{\lfloor (n-1)/(p-1) \rfloor}}.$$

Recently R. M. Wilson used Fleck's congruence and Weisman's extension to present a useful lemma on polynomials modulo prime powers, and applied this lemma to reprove the Ax-Katz theorem on solutions of congruences modulo p and deduce various results on codewords in p -ary linear codes with weights. In light of the recent generalizations of Fleck's congruence given by D. Wan, and D. M. Davis and Z. W. Sun, we obtain new extensions of Wilson's lemma and the Ax-Katz theorem.

1. INTRODUCTION

Let p be a prime, and let $n \in \mathbb{N} = \{0, 1, 2, \dots\}$ and $r \in \mathbb{Z}$. In 1913 A. Fleck (cf. [D, p. 274]) proved that

$$\text{ord}_p \left(\sum_{k \equiv r \pmod{p}} \binom{n}{k} (-1)^k \right) \geq \left\lfloor \frac{n-1}{p-1} \right\rfloor, \quad (1.1)$$

where $\lfloor \cdot \rfloor$ is the well-known floor function, and the p -adic order $\text{ord}_p(\alpha)$ of a p -adic number α is given by $\sup\{a \in \mathbb{Z} : \alpha/p^a \in \mathbb{Z}_p\}$. (As usual \mathbb{Z}_p denotes the ring of p -adic integers in the p -adic field \mathbb{Q}_p .)

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Let $a \in \mathbb{Z}^+ = \{1, 2, 3, \dots\}$. In 1977, motivated by his study of p -adically continuous functions and unaware of Fleck's earlier result, C. S. Weisman [We] extended Fleck's inequality as follows:

$$\text{ord}_p \left(\sum_{k \equiv r \pmod{p^a}} \binom{n}{k} (-1)^k \right) \geq \left\lfloor \frac{n - p^{a-1}}{\varphi(p^a)} \right\rfloor, \quad (1.2)$$

where φ is Euler's totient function.

For a function f from the complex field \mathbb{C} to \mathbb{C} , let $\Delta^0 f(x) = f(x)$, $\Delta f(x) = f(x+1) - f(x)$ and $\Delta^n f(x) = \Delta \Delta^{n-1} f(x)$ for $n = 2, 3, \dots$. Now we recall a classical interpolation formula due to I. Newton and J. Gregory.

Newton-Gregory Interpolation Formula. *Given a function $f : \mathbb{C} \rightarrow \mathbb{C}$, for any $d \in \mathbb{N}$ we have*

$$f(x) = \sum_{n=0}^d c_n \binom{x}{n} + R_d(x),$$

where

$$c_n = \Delta^n f(0) = \sum_{k=0}^n \binom{n}{k} (-1)^{n-k} f(k)$$

and

$$R_d(x) = \frac{\begin{vmatrix} 1 & 0 & \cdots & 0 & f(0) \\ 1 & 1^1 & \cdots & 1^d & f(1) \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & d^1 & \cdots & d^d & f(d) \\ 1 & x^1 & \cdots & x^d & f(x) \end{vmatrix}}{\begin{vmatrix} 1^1 & 1^2 & \cdots & 1^d \\ 2^1 & 2^2 & \cdots & 2^d \\ \cdots & \cdots & \cdots & \cdots \\ d^1 & d^2 & \cdots & d^d \end{vmatrix}}.$$

(Note that $R_d(x) = 0$ if f is a polynomial with $\deg f \leq d$).

In 2006 R. M. Wilson [Wi] rediscovered Weisman's (1.2) in the case $n \equiv p^{a-1} \pmod{\varphi(p^a)}$, and used it to obtain the following lemma (similar to the Newton-Gregory interpolation formula) and give many applications.

Wilson's Lemma. *Let p be a prime, and let $a, b \in \mathbb{Z}^+$. Let f be an integer-valued function on the integers that is periodic modulo p^a . Then there exists a polynomial*

$$w(x) = c_0 + c_1 x + c_2 \binom{x}{2} + \cdots + c_d \binom{x}{d} \quad (c_0, c_1, \dots, c_d \in \mathbb{Z})$$

of degree smaller than $b\varphi(p^a) + p^{a-1}$ such that

$$\text{ord}_p(c_n) \geq \left\lfloor \frac{n - p^{a-1}}{\varphi(p^a)} \right\rfloor \quad \text{for all } n = 0, \dots, d,$$

and $w(x) \equiv f(x) \pmod{p^b}$ for all $x \in \mathbb{Z}$.

In this paper, for a prime p we let $\overline{\mathbb{Q}}_p$ be the algebraic closure of the field \mathbb{Q}_p and let $\overline{\mathbb{Z}}_p$ be the ring of p -adic algebraic integers in $\overline{\mathbb{Q}}_p$. For $m, n \in \mathbb{N}$ we use $[m, n]$ to denote the set $\{x \in \mathbb{Z} : m \leq x \leq n\}$.

In view of the recent generalizations of Fleck's and Weisman's results (cf. [S], [W06], [SW], [DS] and [SD]), we are able to present the following further extension of Wilson's Lemma.

Theorem 1.1. *Let p be a prime, and let $a \in \mathbb{N}$ and $b \in \mathbb{Z}^+$. Let $f(x) \in \overline{\mathbb{Q}}_p[x]$ with $\deg f \leq l \in \mathbb{N}$ and $f(m) \in \overline{\mathbb{Z}}_p$ for all $m \in \mathbb{Z}$, and let g be a function from $[0, p^a - 1]$ to $\overline{\mathbb{Z}}_p$. Let $d \in \mathbb{N}$ be the maximal integer with $M_d < b$, where M_d denotes*

$$\max \left\{ \left\lfloor \frac{d - lp^a - p^{a-1}}{\varphi(p^a)} \right\rfloor, \text{ord}_p \left(\left\lfloor \frac{d}{p^{a-1}} \right\rfloor! \right) - \text{ord}_p(l!) - \min \left\{ l, \left\lfloor \frac{d}{p^a} \right\rfloor \right\} \right\}.$$

Then there exists a polynomial

$$P(x) = \sum_{n=0}^d c_n \binom{x}{n} \quad (c_0, \dots, c_d \in \overline{\mathbb{Z}}_p) \quad (1.3)$$

with $\text{ord}_p(c_n) \geq M_n$ for all $n = 0, \dots, d$, such that

$$P(p^a q + r) \equiv f(q)g(r) \pmod{p^b} \quad \text{for all } q \in \mathbb{Z} \text{ and } r \in [0, p^a - 1]. \quad (1.4)$$

The following celebrated theorem (cf. C. Chevalley [C], E. Warning [Wa] and Theorem 2.6 of M. B. Nathanson [N, pp. 50–51]) is well known and quite useful.

Chevalley-Warning Theorem. *Let $f_1(x, \dots, x_n), \dots, f_m(x_1, \dots, x_n)$ be polynomials over a finite field F of characteristic p with $\deg f_1 + \dots + \deg f_m < n$. Then the number of solutions to the system of equations*

$$f_1(x_1, \dots, x_n) = 0, \dots, f_m(x_1, \dots, x_n) = 0 \quad (1.5)$$

over F^n is a multiple of p .

Here is a further refinement of the Chevalley-Warning theorem due to J. Ax [A] in the case $m = 1$, and N. Katz [K] in the general case.

Ax-Katz Theorem. *Let F_q be the finite field with $q = p^a$ elements where p is a prime and $a \in \mathbb{Z}^+$. Let $f_1(x, \dots, x_n), \dots, f_m(x_1, \dots, x_n)$ be nonzero polynomials over F_q with degrees $d_1 \geq \dots \geq d_m$ respectively. Then, for any positive integer b satisfying $n > (b-1)d_1 + (d_1 + \dots + d_m)$, q^b divides the number of solutions to the system (1.5) over F^n .*

D. Wan [W89, W95] gave a new proof of the Ax-Katz theorem via the Stickelberger theorem. In 2005 X.-D. Hou [H] reduced the Ax-Katz theorem to the Ax theorem on a single polynomial equation. In 2006 Wilson [Wi] reproved the Ax-Katz theorem for prime fields by using Wilson's Lemma.

With help of Theorem 1.1, we establish the following theorem.

Theorem 1.2. *Let p be a prime, and let $F_1(x), \dots, F_m(x) \in \overline{\mathbb{Q}_p}[x]$ with $\deg F_k \leq l_k \in \mathbb{N}$ and $F_k(a) \in \overline{\mathbb{Z}_p}$ for all $a \in \mathbb{Z}$. Let $a_1, \dots, a_m \in \mathbb{N}$, and let $f_1(x_1, \dots, x_n), \dots, f_m(x_1, \dots, x_n)$ be nonzero polynomials with integer coefficients. Assume that $d_1 \varphi(p^{a_1}) = \max_{1 \leq k \leq m} d_k \varphi(p^{a_k})$ where $d_k = \deg f_k$ for $k = 1, \dots, m$. Let $b \in \mathbb{Z}^+$ and suppose that*

$$n > (b-1) \max \left\{ \frac{d_1 \varphi(p^{a_1})}{p-1}, 1 \right\} + \frac{1}{p-1} \sum_{k=1}^m ((l_k+1)p^{a_k} - \llbracket a_k \neq 0 \rrbracket) d_k, \quad (1.6)$$

where $\llbracket a_k \neq 0 \rrbracket$ takes 1 or 0 according as $a_k \neq 0$ or not. Then

$$\sum_{\substack{x_1, \dots, x_n \in [0, p-1] \\ p^{a_k} \mid f_k(x_1, \dots, x_n) \text{ for all } k \in [1, m]}} \prod_{k=1}^m F_k \left(\frac{f_k(x_1, \dots, x_n)}{p^{a_k}} \right) \equiv 0 \pmod{p^b}. \quad (1.7)$$

In the case $F_1(x) = \dots = F_m(x) = 1$, Theorem 1.2 yields an extension of the Ax-Katz theorem for prime fields. In 1995 O. Moreno and C. J. Moreno [MM] introduced a method to reduce the general case of the Ax-Katz theorem to the prime field case.

Corollary 1.1. *Let $f_1(x_1, \dots, x_n), \dots, f_m(x_1, \dots, x_n)$ be nonzero polynomials with integer coefficients having degrees $d_1 \geq \dots \geq d_m$ respectively. If p is a prime, $a, b \in \mathbb{Z}^+$, $l_1, \dots, l_m \in \mathbb{N}$ and*

$$n > (b-1)d_1 p^{a-1} + \frac{p^a - 1}{p-1} \sum_{k=1}^m d_k + \frac{p^a}{p-1} \sum_{k=1}^m l_k d_k, \quad (1.8)$$

then we have

$$\sum_{\substack{x_1, \dots, x_n \in [0, p-1] \\ p^a \mid f_k(x_1, \dots, x_n) \text{ for all } k \in [1, m]}} \prod_{k=1}^m \left(\frac{f_k(x_1, \dots, x_n)/p^a}{l_k} \right) \equiv 0 \pmod{p^b}. \quad (1.9)$$

Proof. Just apply Theorem 1.2 with $a_k = a$ and $F_k(x) = \binom{x}{l_k}$ for $k = 1, \dots, m$. \square

Let $q = p^a$ where p is a prime and $a \in \mathbb{Z}^+$, and let $\zeta_{q-1} \in \overline{\mathbb{Z}}_p$ be a primitive $(q-1)$ -th roots of unity. It is well known that $\mathbb{Z}_p[\zeta_{q-1}]/(p)$ is a finite field of q elements. The finite field \mathbb{F}_q of $q = p^a$ elements is an extension of the prime field \mathbb{F}_p with $[\mathbb{F}_q : \mathbb{F}_p] = a$. Thus \mathbb{F}_q is isomorphic to \mathbb{F}_p^a and the Chevalley-Warning theorem can be reduced to the prime field case. Corollary 1.1 in the case $a = b = 1$ and $l_1 = \dots = l_m = 0$ yields the Chevalley-Warning theorem for $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ and hence the general case of the Chevalley-Warning theorem.

2. PROOFS OF THEOREMS 1.1 AND 1.2

Lemma 2.1. *Let p be a prime, and let $f(x) \in \overline{\mathbb{Q}}_p[x]$ with $\deg f \leq l \in \mathbb{N}$ and $f(m) \in \overline{\mathbb{Z}}_p$ for all $m \in \mathbb{Z}$. For any $a, n \in \mathbb{N}$ and $r \in \mathbb{Z}$, we have*

$$\text{ord}_p \left(\sum_{k \equiv r \pmod{p^a}} \binom{n}{k} (-1)^k f \left(\frac{k-r}{p^a} \right) \right) \geq \left\lfloor \frac{n - lp^a - p^{a-1}}{\varphi(p^a)} \right\rfloor \quad (2.1)$$

and

$$\begin{aligned} & \text{ord}_p \left(\sum_{k \equiv r \pmod{p^a}} \binom{n}{k} (-1)^k f \left(\frac{k-r}{p^a} \right) \right) \\ & \geq \text{ord}_p \left(\left\lfloor \frac{n}{p^{a-1}} \right\rfloor! \right) - \text{ord}_p(l!) - \min \left\{ l, \left\lfloor \frac{n}{p^a} \right\rfloor \right\}. \end{aligned} \quad (2.2)$$

Proof. Let $c_j = \sum_{i=0}^j \binom{j}{i} (-1)^{j-i} f(i) \in \overline{\mathbb{Z}}_p$ for $j = 0, \dots, l$. As $\deg f \leq l$ and $f(x) - \sum_{j=0}^l c_j \binom{x}{j}$ vanishes at $0, \dots, l$, we have $f(x) = \sum_{j=0}^l c_j \binom{x}{j}$. So it suffices to consider the case $f(x) = \binom{x}{l}$ only.

If $a \in \mathbb{Z}^+$ then

$$O := \text{ord}_p \left(\sum_{k \equiv r \pmod{p^a}} \binom{n}{k} (-1)^k \binom{(k-r)/p^a}{l} \right) \geq \left\lfloor \frac{n - lp^a - p^{a-1}}{\varphi(p^a)} \right\rfloor$$

by D. Wan [W06, Theorem 1.3] (see also [SW] for a combinatorial proof). This is also true in the case $a = 0$, since

$$\sum_{k=0}^n \binom{n}{k} (-1)^k \binom{k-r}{l} = \mathbb{I}[l \geq n] (-1)^n \binom{-r}{l-n}$$

by a known identity (cf. [GKP, (5.24)]).

As $l! \binom{x}{l} \in \mathbb{Z}[x]$, by [DS, Theorem 1.5] we have

$$O + \text{ord}_p(l!) \geq \text{ord}_p \left(\left\lfloor \frac{n}{p^a} \right\rfloor! \right) = \sum_{s=a+1}^{\infty} \left\lfloor \frac{n}{p^s} \right\rfloor = \text{ord}_p \left(\left\lfloor \frac{n}{p^{a-1}} \right\rfloor! \right) - \left\lfloor \frac{n}{p^a} \right\rfloor.$$

By [SD, Theorem 1.2], we also have

$$O \geq \text{ord}_p \left(\left\lfloor \frac{n}{p^{a-1}} \right\rfloor! \right) - l - \text{ord}_p(l!).$$

Combining the above we obtain both (2.1) and (2.2). \square

Proof of Theorem 1.1. Let $F(x) = f(\lfloor x/p^a \rfloor)g(\{x\}_{p^a})$ for $x \in \mathbb{Z}$, where $\{x\}_{p^a}$ denotes the least nonnegative residue of x modulo p^a . For

$$\begin{aligned} c_n &:= \sum_{k=0}^n \binom{n}{k} (-1)^{n-k} F(k) \\ &= (-1)^n \sum_{r=0}^{p^a-1} g(r) \sum_{k \equiv r \pmod{p^a}} \binom{n}{k} (-1)^k f\left(\frac{k-r}{p^a}\right), \end{aligned}$$

we have $\text{ord}_p(c_n) \geq M_n$ by Lemma 2.1. If $n > d$, then $\text{ord}_p(c_n) \geq M_n \geq b$. Set $P(x) = \sum_{n=0}^d c_n \binom{x}{n}$. Then, for each $m \in \mathbb{N}$ we have

$$\begin{aligned} F(m) &= \sum_{k=0}^m \binom{m}{k} F(k) (1-1)^{m-k} = \sum_{k=0}^m \binom{m}{k} F(k) \sum_{n=k}^m \binom{m-k}{n-k} (-1)^{n-k} \\ &= \sum_{n=0}^m \binom{m}{n} \sum_{k=0}^n \binom{n}{k} (-1)^{n-k} F(k) = \sum_{n \in \mathbb{N}} \binom{m}{n} c_n \\ &\equiv \sum_{n=0}^d \binom{m}{n} c_n = P(m) \pmod{p^b}. \end{aligned}$$

Therefore $P(p^a q + r) \equiv F(p^a q + r) = f(q)g(r) \pmod{p^b}$ for all $q \in \mathbb{N}$ and $r \in [0, p^a - 1]$.

Choose $N \in \mathbb{N}$ such that $N - b \geq \text{ord}_p(k)$ for all $k \in [1, \max\{d, l\}]$. For any $x \in \mathbb{Z}$ and $n \in [0, \max\{d, l\}]$, by the Chu-Vandermonde convolution identity (cf. [GKP, (5.27)]) we have

$$\begin{aligned} \binom{x + p^N}{n} &= \sum_{k=0}^n \binom{p^N}{k} \binom{x}{n-k} \\ &= \binom{x}{n} + \sum_{0 < k \leq n} \frac{p^N}{k} \binom{p^N - 1}{k-1} \binom{x}{n-k} \equiv \binom{x}{n} \pmod{p^b}. \end{aligned}$$

Therefore $P(x + p^N) \equiv P(x) \pmod{p^b}$ and $f(x + p^N) \equiv f(x) \pmod{p^b}$ for all $x \in \mathbb{Z}$. For $m = -p^a q + r$ with $q \in \mathbb{Z}^+$ and $r \in [0, p^a - 1]$, clearly

$m + p^{a+q+N} \geq 0$ and hence

$$\begin{aligned} P(m) &\equiv P(m + p^{a+q+N}) \equiv F(m + p^{a+q+N}) \\ &\equiv f\left(\left\lfloor \frac{m}{p^a} \right\rfloor + p^{q+N}\right) g(\{m\}_{p^a}) \\ &\equiv f\left(\left\lfloor \frac{m}{p^a} \right\rfloor\right) g(\{m\}_{p^a}) = F(m) \pmod{p^b}. \end{aligned}$$

By the above, we do have $P(p^a q + r) \equiv F(p^a q + r) = f(q)g(r) \pmod{p^b}$ for all $q \in \mathbb{Z}$ and $r \in [0, p^a - 1]$. \square

Lemma 2.2. *Let p be a prime, and let*

$$F(x_1, \dots, x_n) = \binom{f_1(x_1, \dots, x_n)}{j_1} \cdots \binom{f_m(x_1, \dots, x_n)}{j_m},$$

where $j_k \in \mathbb{N}$ and $f_k(x_1, \dots, x_n) \in \overline{\mathbb{Z}}_p[x_1, \dots, x_n]$ for $k = 1, \dots, m$. If the total degree of $F(x_1, \dots, x_n)$ is smaller than $(n - c + 1)(p - 1)$ for some $c \in \mathbb{N}$, then

$$\sum_{x_1, \dots, x_n \in [0, p-1]} F(x_1, \dots, x_n) \equiv 0 \pmod{p^c}.$$

Proof. See Lemma 4 of Wilson [Wi] and its proof. \square

Proof of Theorem 1.2. Given $k \in [1, m]$, by Theorem 1.1 there is a polynomial

$$P_k(x) = \sum_{j=0}^{n_k} c_j^{(k)} \binom{x}{j} \quad (c_1^{(k)}, \dots, c_{n_k}^{(k)} \in \overline{\mathbb{Z}}_p)$$

such that

$$\text{ord}_p(c_j^{(k)}) \geq \left\lfloor \frac{j - l_k p^{a_k} - p^{a_k-1}}{\varphi(p^{a_k})} \right\rfloor$$

for all $j = 0, \dots, n_k$, and

$$P_k(x) \equiv \llbracket p^{a_k} \mid x \rrbracket F_k\left(\frac{x}{p^{a_k}}\right) \pmod{p^b} \quad \text{for all } x \in \mathbb{Z}.$$

Therefore

$$\begin{aligned} &\sum_{\substack{x_1, \dots, x_n \in [0, p-1] \\ p^{a_k} \mid f_k(x_1, \dots, x_n) \text{ for all } k \in [1, m]}} \prod_{k=1}^m F_k\left(\frac{f_k(x_1, \dots, x_n)}{p^{a_k}}\right) \\ &\equiv \sum_{x_1, \dots, x_n \in [0, p-1]} \prod_{k=1}^m P_k(f_k(x_1, \dots, x_n)) \\ &\equiv \sum_{j_1=0}^{n_1} c_{j_1}^{(1)} \cdots \sum_{j_m=0}^{n_m} c_{j_m}^{(m)} S(j_1, \dots, j_m) \pmod{p^b}, \end{aligned}$$

where

$$S(j_1, \dots, j_m) = \sum_{x_1, \dots, x_n \in [0, p-1]} \prod_{k=1}^m \binom{f_k(x_1, \dots, x_n)}{j_k}.$$

Fix $j_1 \in [0, n_1], \dots, j_m \in [0, n_m]$, and let

$$\alpha_k = \max \left\{ \left\lfloor \frac{j_k - l_k p^{a_k} - p^{a_k-1}}{\varphi(p^{a_k})} \right\rfloor, 0 \right\} \quad \text{for } k = 1, \dots, m.$$

Then

$$\text{ord}_p \left(c_{j_1}^{(1)} \cdots c_{j_m}^{(m)} \right) = \sum_{k=1}^m \text{ord}_p \left(c_{j_k}^{(k)} \right) \geq \sum_{k=1}^m \alpha_k.$$

So it suffices to show that $\text{ord}_p(S(j_1, \dots, j_m)) \geq c = b - \sum_{k=1}^m \alpha_k$.

Assume that $c > 0$. By the definition of α_k , $j_k - l_k p^{a_k} - p^{a_k-1} < (\alpha_k + 1)\varphi(p^{a_k})$ and hence

$$j_k \leq l_k p^{a_k} + (\alpha_k + 1)\varphi(p^{a_k}) + \llbracket a_k \neq 0 \rrbracket (p^{a_k-1} - 1).$$

Thus

$$\begin{aligned} \sum_{k=1}^m j_k d_k &\leq \sum_{k=1}^m (l_k p^{a_k} + \llbracket a_k \neq 0 \rrbracket (p^{a_k-1} - 1) + (\alpha_k + 1)\varphi(p^{a_k})) d_k \\ &= \sum_{k=1}^m (l_k p^{a_k} + p^{a_k} - \llbracket a_k \neq 0 \rrbracket + \alpha_k \varphi(p^{a_k})) d_k \\ &\leq \sum_{k=1}^m ((l_k + 1)p^{a_k} - \llbracket a_k \neq 0 \rrbracket) d_k + \varphi(p^{a_1}) d_1 \sum_{k=1}^m \alpha_k \end{aligned}$$

and hence

$$\begin{aligned} \sum_{k=1}^m j_k d_k &< n(p-1) - (b-1) \max \{d_1 \varphi(p^{a_1}), p-1\} + (b-c)d_1 \varphi(p^{a_1}) \\ &\leq n(p-1) - (c-1) \max \{d_1 \varphi(p^{a_1}), p-1\}. \end{aligned}$$

Therefore

$$\deg \prod_{k=1}^m \binom{f_k(x_1, \dots, x_n)}{j_k} \leq \sum_{k=1}^m j_k d_k < (p-1)(n-c+1)$$

and hence $S(j_1, \dots, j_m) \equiv 0 \pmod{p^c}$ by Lemma 2.2. This concludes the proof. \square

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